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RECYCLED AGGREGATE CONCRETE EXPOSED TO ELEVATED TEMPERATURE

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ABSTRACT

An experimental investigation was conducted to study the mechanical as well as micro structural properties of recycled aggregate concrete (RAC) exposed to elevated temperature. Fly ash (as replacement of cement) was added while making concrete. Recycled aggregates are mixed with natural aggregates also to prepare concrete. Cubes and cylinder test specimens were prepared and cured under water for 28 days. Test specimens were exposed to different levels of temperature (200°C, 400°C, 600°C, 800°C, 1000°C) for a period of 6 hours in the furnace. The reduction in compressive strength observed are in the ranges from 21% to as high as 61% when exposed to elevated temperature. Modulus of elasticity reduces appreciably also with the increase of exposure temperature. MIP (Mercury intrusion porosimetry) test was conducted to estimate the percentage of voids and also to appreciate the change of micro voids due to change of exposure temperature. Microscopic study was made to note the change of surface texture. Empirical formulae involving major parameters such as fly ash content, exposure temperature etc. have been developed to predict modulus of elasticity of recycled aggregate concrete.

Keywords: recycled aggregate concrete, fly ash, elevated temperature, modulus of elasticity, mercury intrusion porosimetry, strength.

INTRODUCTION

Concrete using recycled coarse aggregate from waste concrete is now a popular subject of research. Green concept of construction leads the construction industry to use the materials of low embodied energy and also the materials which reduces the destabilization of environment. Recycled aggregate satisfies both the requirement. Some research works on strength aspect of cement with Fly ash has been observed and studied at elevated temperature also. The test results are compared with similar Natural aggregate concrete (NAC). This kind of study on RAC has not received attention in the past. Generally high temperature causes an abrupt physical and chemical change in concrete [1]. Empirical formulae are derived to predict modulus of elasticity of recycled aggregate concrete with varying percent of fly ash replacement and exposure temperature. Change of pore volume in concrete mix before and after heating is also determined with the help of Mercury intrusion porosimetry technique (MIP).

EXPERIMENTAL DETAILS

Materials

Cement: Ordinary Portland cement of Grade 53 Conforming to IS 12269-1987 [7]**.**

Fine aggregate: Locally available natural sand of Zone III as per IS 383-1970 [8].

Coarse aggregate: Two types of coarse aggregate were used i) Natural stone aggregate of Basalt variety ii) Laboratory waste aggregate processed from Laboratory waste concrete cubes of 150mm x 150mm x 150mm of mean compressive strength 23.53 MPa.

The aggregate was divided into two fractions which are Type-I and Type-II. The fraction of coarse aggregate passing through 40mm of IS sieve and retain on 20mm of IS sieve was termed as Type-I and the fraction of coarse aggregate passing through 20mm of IS sieve and retained on 4.75mm of IS sieve was Type-II.

Fly ash: The fly ash was directly obtained from Bandel near Kolkata. The chemical composition of fly ash is shown in Table-1 below. Specification of fly ash as prescribed by IS 3812 - Part-I [9] are also compared.

Table-1. Chemical composition of fly ash.

Chemical properties	**Properties of fly ash weight** (%)	**Specified requirement weight** (%) **IS-3812 -part-I**
SiO_2	60.0	35.0 minimum
Al_2O_3	20.0	
CaO	8.0	
MgO	1.0	5.0 maximum
TiO_2	0.5	
Loss of ignition	8.0	12.0 maximum
Na_2O/K_2O	1.0	

Concrete Mix: There is no standard mix design procedure for recycled aggregate concrete. Hence, trial mixes as per ACI [10] for natural aggregate concrete (NAC) was adopted. Five different mixes were prepared as shown in Table-2. In some mixes of RAC certain percent of cement was replaced by fly ash like in RAC+10F mix, 10% cement was replaced by fly ash. Similarly in RAC+20F mix, 20% cement was replaced by fly ash. In NAC + RAC mix, 50% natural aggregate is replaced by recycled aggregate.

Table-2. Mix proportion.

Mix No.	Mix	Mix proportion (by weight)					
		Cement	Fly ash	Sand	Coarse aggregates		Water cement ratio
					Type I	Type II	
1	NAC	1.00	-	2.19	0.83	1.25	0.5
2	NAC+ RAC	1.00	-	2.19	0.83	1.25	0.5
3	RAC	1.00	-	2.19	0.83	1.25	0.5
4	RAC+ 10F	0.90	0.1	2.19	0.83	1.25	0.5
5	RAC+ 20F	0.80	0.2	2.19	0.83	1.25	0.5

Specimen casting, curing and testing: Thirty six standard cubes of size 150mm x 150mm x 150mm for each mix (i.e., total one hundred eighty cubes) and seventy two standard cylinders of size 150mm diameter x 300mm high for each mix a (total three hundred sixty cylinders) were cast. The specimens were then cured under water for 28 days. Specimen was heated in a furnace at 200^{o}C, 400^{o}C, 600^{o}C, 800^{o}C and 1000^{o}C temperature for 6 hrs. Compressive strength was determined by testing cubes and cylinder to destruction. Stress vs. Strain plots were also studied. Six cubes and twelve cylinders were cast from each mix and tested at a particular temperature.

RESULTS AND DISCUSSIONS

Behavior of Concrete before and after heating

It is observed that the compressive strength of NAC is highest among other types of concrete. RAC has approximately 19% lower cube compressive strength than NAC. Similar results were also reported by other researchers [2,3]. But it is also observed that this reduction of strength can be avoided to some extent by using optimal quantity of fly ash replacement in RAC. RAC+10F mix shows an increment of cube compressive strength of 9.5% and 8% increment in case of cylinder strength. Tables 3 and 4 indicate the cube compressive strength and cylinder compressive strength.

Table-3. Cube compressive strength.

S l	Mix	Strength in MPa					
		27^{o}C *	200^{o}C	400^{o}C	600^{o}C	800^{o}C	1000^{o}C
1	NAC	30.1	23.7	22.8	22.3	21.0	13.63
2	NAC+ RAC	27.7	21.6	20.3	18.7	18.5	12.6
3	RAC	24.9	19.3	17.5	16.7	13.9	9.63
4	RAC + 10F	27.3	21.0	19.9	19.4	18.1	12.00
5	RAC + 20F	23.4	18.4	16.1	14.5	13.3	9.5

* 27 ^{o}C - Room temperature

Table-4. Cylinder strength.

S l	Mix	Strength in MPa					
		27^{o}C*	200^{o}C	400^{o}C	600^{o}C	800^{o}C	1000^{o}C
1	NAC	26.4	20.2	18.9	16.8	6.0	4.5
2	NAC+RAC	20.9	12.5	12.4	11.7	5.1	3.6
3	RAC	19.0	13.0	10.2	5.84	5.7	2.6
4	RAC + 10F	20.6	15.5	10.9	5.8	4.7	3.0
5	RAC + 20F	13.9	11.1	10.8	8.1	2.1	1.2

* 27 ^{o}C - Room temperature

After heating to different temperature it is seen that the reduction of cube strength for all types of concrete at 200^{o}C ranges from 21.2% to 23.1% which after heating at 600^{o}C rises to 25.9% to 38%. Again, after 1000^{o}C average loss of compressive strength is 55% for NAC where as for RAC it is around 61%. At all temperature level percent reduction of strength is smaller in NAC compare to the other mix. This is due to the stronger interfacial bonding between matrix and aggregate. In RAC as there is an old mortar attached to the aggregate which lead to porous and loose interfacial zone [4] and responsible for rapid reduction in strength. But when an optimal percent of fly ash (10%) is added to RAC, the performance of this mix is better than RAC as it modifies the transition zone i.e., more precisely it modifies the microstructure of the interfacial zone. This is observed even after exposing concrete to elevated temperature.

Stress vs strain behaviour

To study stress vs strain behavior of different types concrete before and after exposition to elevated temperature. Cylinder specimens were tested under direct compression with prefixed controlled rate of loading and corresponding axial deformation was measured. Linear curves fitting were then made. Typical such graph is shown in Figure-1. From these graphs modulus of elasticity has been obtained (Table-5). It is observed that concrete offers less modulus of elasticity value when exposed to higher temperature. From Table-5, it is observed that at normal temperature E value of RAC is 16.8% lower than NAC but with 10% fly-ash replacement RAC+10F regains E value around 9.6%.

At higher temperature also the E value of RAC+10F is higher than RAC. The change in E value after heating at 200°C ranges from 18.3% to 48.6% but after 400°C the change is very abrupt and at 800°C as high as 92%. This is because at higher temperature the micro structure of concrete becomes weaken which reduces the strength of the concrete as well as abrupt reduction in E value occurs.

At all the cases it is observed that the maximum strain of NAC is much lower than other mix. Maximum strain attains by RAC+20F which is even greater than RAC but RAC+10F shows a lower strain than RAC. By Mercury intrusion test method it is observed that at unheated condition total pore volume of RAC is 8.4% where as RAC +10F mix contains 5.2% only, which means that the fly ash replacement in the RAC mix densify the matrix which leads to a reduction in total pore volume resulting reduction in strain in concrete.

From the Stress Vs Strain graph it is also clear that at higher temperature strain of concrete is higher irrespective of concrete mix. Similar results were also reported by other researchers in different concrete like high performance concrete [5, 6]. At higher temperature micro-cracks develops in concrete (Figures 7 and 8) which causes reduction in strength and also higher strain.

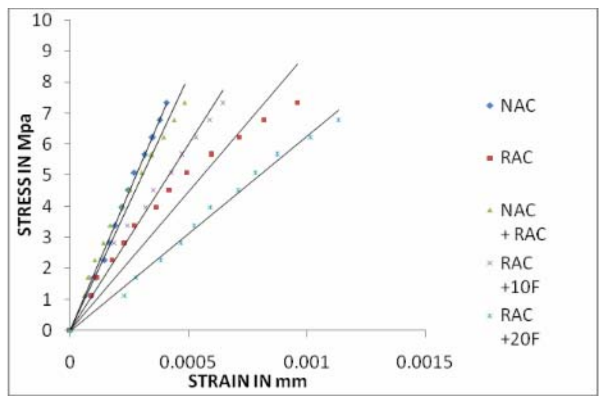

Figure-1. Typical stress vs. strain of natural and recycled aggregate concrete at 200°C temperature (with and without fly ash)

Table-5. E value of concrete after exposing different temperature.

	NAC	NAC+RAC	RAC	RAC+10F	RAC+20F
ROOM TEMP (27°C)	28571.43	26666.67	23750.00	25833.33	17500.00
200°C	23333.33	22857.14	13333.00	17500.00	9000.00
400°C	22500.00	20000.00	9500.00	12667.00	7000.00
600°C	4250.00	3500.00	2580	2812	1583
800°C	2500.00	2250.00	2400	2687	1400

The relation between compressive strength of concrete, percent fly ash replacement and temperature at which the samples were exposed are assumed as follows:

$\bar{E} \propto f_{ck}\, f_a / \check{T}$

$\bar{E} = \acute{\eta}\, f_{ck}\, f_a / \check{T}$ ------ (1)

Where,

$\bar{E}$ = Calculated E value of concrete

$\acute{\eta}$ = Constant of proportionality

f_{ck} = Compressive strength of recycled concrete

f_a = % flyash in RAC sample

$\check{T}$ = Temperature in °C at which the samples were exposed.

From Figures 2 to 4 we got the regression equations of different relation between the above factors, the temperature range considered up to 400°C.

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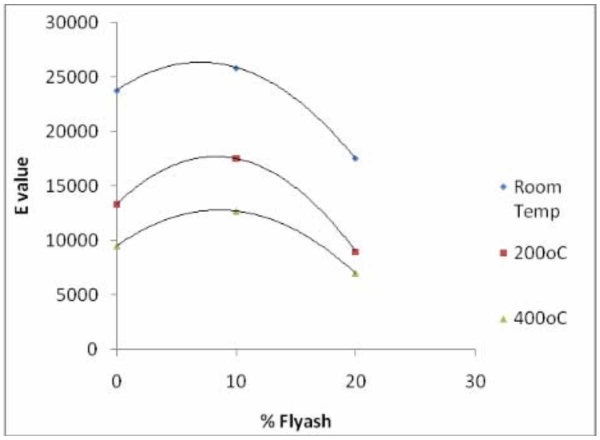

Figure-2. E values of RAC samples vs % flyash in RAC at different elevated temperature.

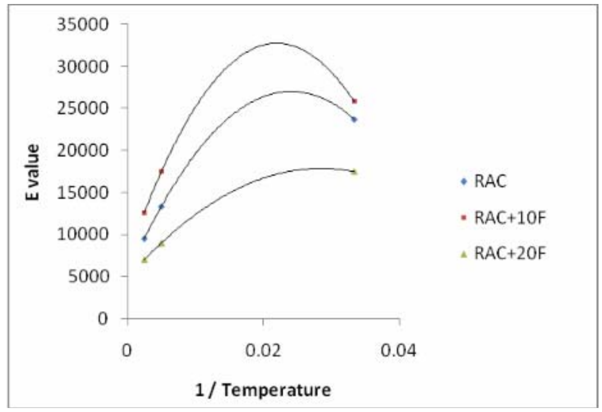

Figure-3. E values of RAC samples vs 1/ temperature at which the samples were exposed.

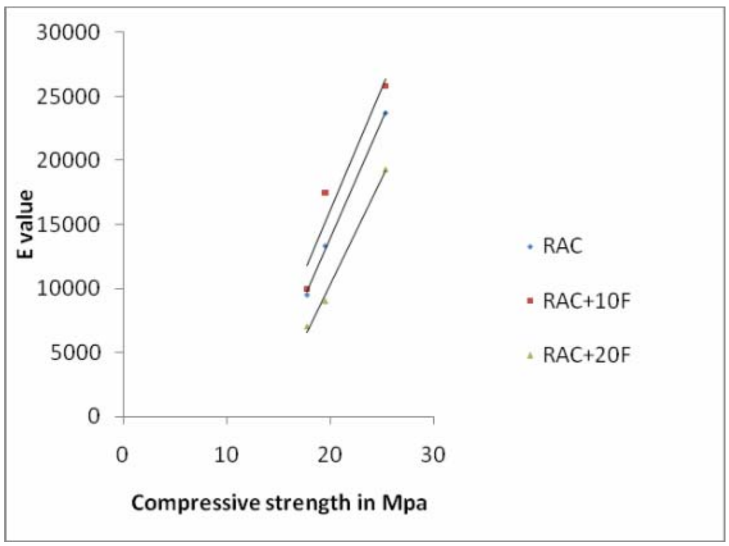

Figure-4. E values of RAC samples vs. compressive strength at different elevated temperature.

From Figure-2, by regression analysis

$\bar{E} = K_1 fa^2 + K_2 fa + K_3$ --------------- (2)

Where,

$K_1 = -63.33$, $K_2 = 1050$, $K_3 = 13333$

From Figure-3, by regression analysis

$\bar{E} = K_4 (1/ \check{T})^2 + K_5 (1/ \check{T}) + K_6$ --------------- (3)

Where,

$K_4 = -1E^{+8,}$ $K_5 = 5E^{+6,}$ $K_6 = 5321$

From Figure-4, by regression analysis

$\bar{E} = K_7 f_{ck} - K_8$ ----------- (4)

Where,

$K_7 = 1875$, $K_8 = -23655$

Combining regression equations from Figures 2, 3 and 4 as per eqn. (1)

$\bar{E} = ή [(K_1 fa^2 + K_2 fa + K_3) (K_7 f_{ck} - K_8) / (K_4 (1/ \check{T})^2 + K_5 (1/ \check{T}) + K_6)]$ -------------- (5)

Or, $ή = \bar{E} / \breve{E}$

Where,

$\breve{E} = [(K_1 fa^2 + K_2 fa + K_3) (K_7 f_{ck} - K_8) / (K_4 (1/ \check{T})^2 + K_5 (1/ \check{T}) + K_6)]$

From the above equation, average value of ή is calculated ή = -0.39

Which reduces the eqn. (5) as follows:

$\bar{E} = -0.39 \ [(K_1 fa^2 + K_2 fa + K_3) (K_7 f_{ck} - K_8) / (K_4 (1/ \check{T})^2 + K_5 (1/ \check{T}) + K_6)]$ ------------- (6)

The above equation is valid up to 400^oC.

Computing average ή, derived value of modulus of elasticity from above relation is computed below:

Table-6. Comparison of predicted and experimental E values of concrete (Up to 400°C).

Mix	Temp	Value of modulus of elasticity (E)		% deviation
		Predicted from Eqn (6)	Exp. value	
RAC	Room 27°C.	23566.99	23750.00	-0.77
	200°C	12735.35	13333	-4.48
	400°C	9538.27	9500	0.40
RAC +10F	Room 27°C.	30932.44	25833.33	19.74
	200°C	16715.57	17500	-4.48
	400°C	12519.29	12667	-1.17
RAC+20F	Room 27°C	15909.9	17500	-9.09
	200°C	8597.53	9000	-4.47
	400°C	6439.21	7000	-8.0

It is observed that the value of modulus of elasticity calculated from the derived formula tallies with the experimental results, the variations for most of the cases are only -9% to 0.4% except in one case where it was around 19%. So the relation could be used to predict the modulus of elasticity of Recycled aggregate concrete of different mixes.

From similar calculation on samples which were exposed temperature range above 400°C

Ē = ή1 [(K9 fa2 + K10 fa + K11) (K14fck-K15) / (K12 (1/Ť) + K13)] ---------------- (7)

Where

K9 = -7.06, K10 = 93.75, K11 = 2580

K12 = 30000, K13 = 2312

K14 = 69.963, K15 = 1630

And average ή1 =0 .87

Table-6A shows the calculated value and value obtained from experiment.

Table-6 A. Comparison of predicted and experimental E values of concrete (above 400°C).

Mix	Temp	Value of modulus of elasticity (E)		% deviation
		Predicted from Eqn. (7)	Exp. value	
RAC	600°C	2305.6	2615	-11.8
	800°C	2733	2400	13.9
RAC + 10F	600°C	2512.9	2800	-10.2
	800°C	2979.4	2700	10.3
RAC + 20F	600°C	1459.3	1667	-12.44
	800°C	1730.2	1500	15.3

Here the variations are -12 to +15%.

Microscopic study of surface texture

Figures 5, 6, 7 and 8 shows the texture of the concrete samples of RAC and RAC+10F before and after heating, respectively. After heating to an elevated temperature the texture of the sample becomes coarse and several micro cracks appeared, which gradually worsen the strength character of the sample.

The water attached to the microstructure after heating at high temperature evaporated and pores in microstructure gradually increases which causes higher linear deformity of the concrete with load.

It is observed from the above photographs that the micro cracks in RAC+10F sample are much less in compare with RAC sample after heating to 800°C, which explains the higher strength of RAC+10F mix than RAC mix.

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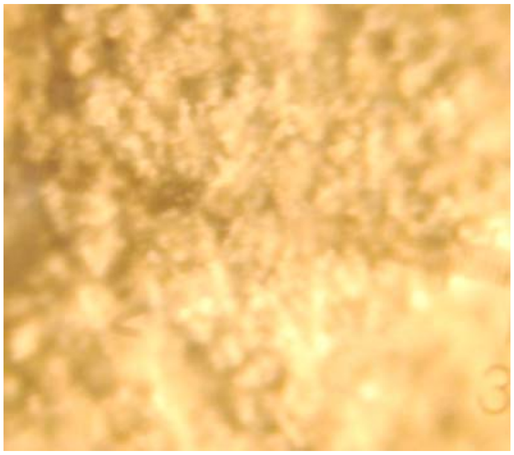

Figure-5. Microscope study of concrete sample (RAC) before heating.

Figure-6. Microscope study of concrete sample (RAC) after heating at 800°C.

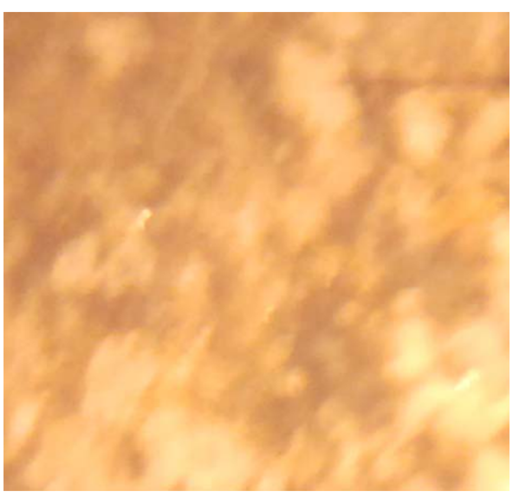

Figure-7. Microscope study of concrete sample (RAC+10F) before heating.

Figure-8. Microscope study of concrete sample (RAC +10F) after heating at 800°C.

Murcury intrusion porosimetry (MIP)

To determine the total porosity volume of the concrete mix, sample of RAC and RAC+10F at normal and same sample after heating at 800°C was taken and Mercury Porosimeter was used for the test. In the instrument approximate 383 MPa pressure was produced to cover the pore diameter in the range of .004 µm to 378µm.

Figure-9. Shows the total volume of pore in RAC and RAC+10F at normal temperature. Total volume of pore in RAC is 8.45% where as in RAC+10F it is 5.2%. These results explain the improvement of compressive strength and smaller strain of RAC+10F compare to RAC.

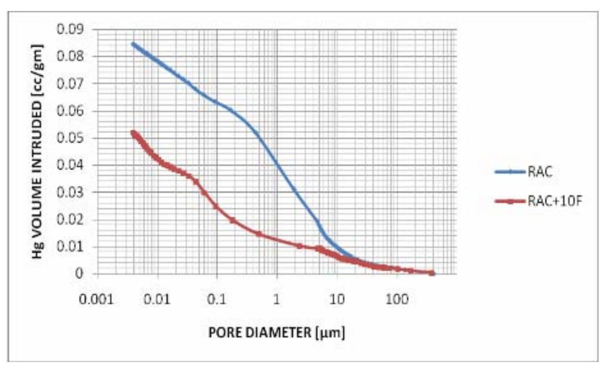

Figure-9. Comparison of intruded Hg volume Vs pore diameter curve for RAC and RAC+10F before heating.

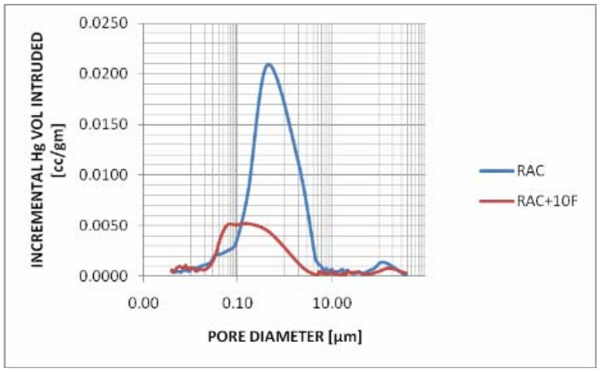

Figure-10. Comparison of incremental intrusion of Hg volume Vs pore diameter curve for RAC and RAC+10F before heating.

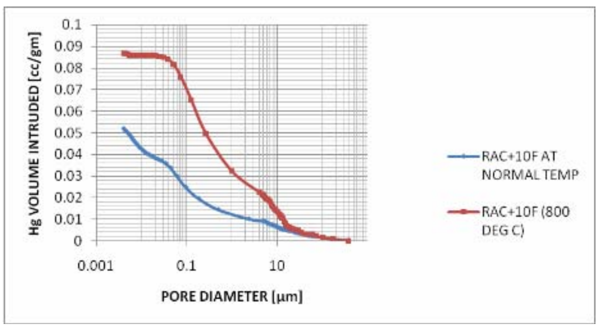

Figure-11. Comparison of intruded Hg volume Vs pore diameter curve for RAC+10F at normal temp and RAC+10F after heating at 800°C.

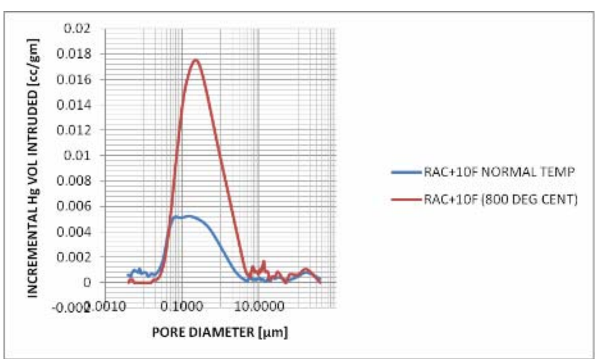

Figure-12. Comparison of incremental intrusion of Hg volume Vs pore diameter curve for RAC+10F at normal temp and RAC+10F after heating at 800°C.

Figures 11 and 12 represents the increment of pore volume in concrete mix due to temperature, here RAC+10F at normal temperature and after heating at 800°C has been compared. This graph shows in RAC+10F sample at normal temperature the total pore volume is 5.2% and major pore diameter lies between .04 µm to 1µm, RAC+10F sample after heating to 800°C total pore volume of the sample increases to 8.67% leads to a coarser microstructure. The increment of total pore volume after heating is around 67% compare to the sample at normal temperature, which explains the reduction in strength and modulus of elasticity at high temperature.

Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) was done on the sample of RAC, RAC+10F and RAC+20F after exposure to 800°C. Figures 13, 14 and 15 shows the condition of microstructure of these samples. It is observed from photographs that the microstructure in RAC+10F is much denser in comparison with RAC and RAC+20F sample. Which also confirms the result of strength and stress strain behavior of the samples.

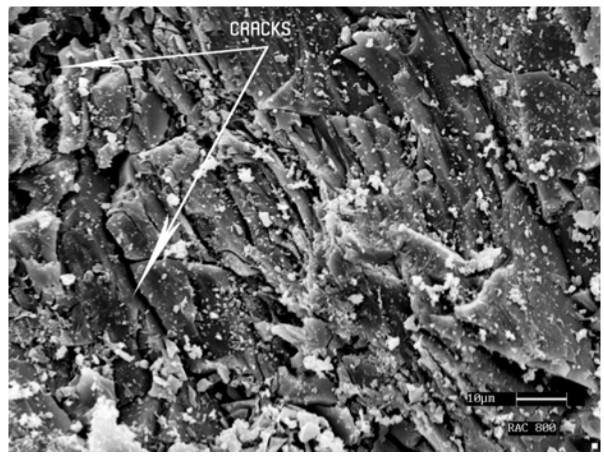

Figure-13. Microstructure study of RAC through SEM after heating at 800°C.

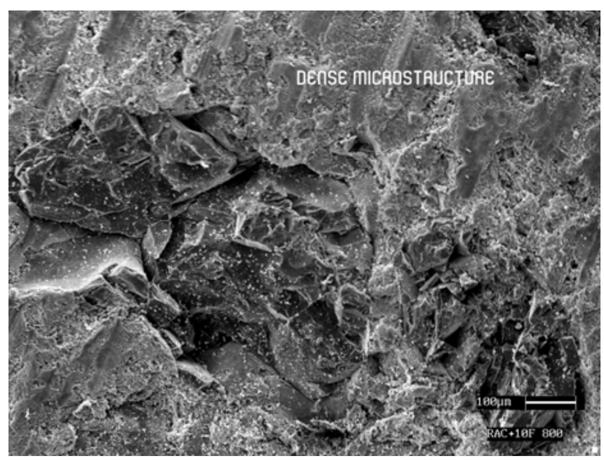

Figure-14. Microstructure study of RAC +10F through SEM after heating at 800°C.

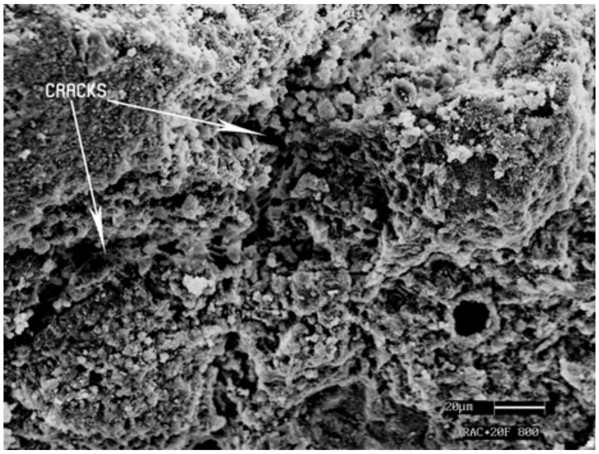

Figure-15. Microstructure study of RAC +20F through SEM after heating at 800^{o}C.

CONCLUSIONS

Above discussion about effect of elevated temperature on concrete leads to the following conclusions:

a) In general RAC sample unheated and after heating at different elevated temperature shows an inferior behavior compare to NAC;
b) Among different Fly ash replacement percentage, 10% Fly ash replacement shows a better performance compare to 20% Fly ash replacement;
c) It is also revealed that total pore volume of a concrete mix increases after exposure to an elevated temperature;
d) 10% replacement of cement with fly ash improves the micro structure of the concrete which improves the strength character of recycled aggregate concrete;
e) Murcury intrusion test shows that total pore volume in RAC is much higher than RAC+10F at ordinary condition; and
f) Over all degradation of concrete after heating to an elevated temperature broadly due to:

a. Microstructure of concrete becomes coarser due to high temperature [3].
b. Total pore volume increases after heating, which leads to higher strain in concrete as well as lower compressive strength.

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